

Per Zone Variable BPI for Improving Storage Device Capacity and Yield

By

Saeed Asgari

Mathew Veal

And

George Iszlai

Field of the Invention

The present invention relates generally to the storage of information on fixed storage media, and more particularly to improving storage of information on rotating magnetic media such as disks in a disk drive.

Background of the Invention

Data storage devices such as disk drives are used in many data processing systems for data storage. Typically a disk drive includes a magnetic data disk having recording surfaces with concentric data tracks, and a transducer head paired with each recording surface, for writing data to, and reading data from, the data tracks. Each paired magnetic head and media surface couples to provide a unique data recording capability which depends on the fly height of the head from the recording surface, the quality/distribution of magnetic media on the recording surface, and the magnetic properties of the magnetic head.

Conventional methods of recording data using the paired head and recording surface are inefficient because they do not take into consideration the differences in data recording capabilities between one pair of head and recording surface, and another head and surface pair. Though the heads are designed to perform identically in read/write operations, in practice different heads in a disk drive can have different read/write performance capabilities. Lower performing heads cannot read/write data as that of other heads in the disk drive. Typically, a single error rate level and a single storage capacity level are used to record data for all the pair heads and surfaces. This results in inefficient data storage for

those pairs of heads and surfaces that can store more data. It also lowers the qualification yields of the disk drives because one or more pairs of heads and surfaces do not record data at the qualifying error rate and capacity levels.

Further, in high data rate design of disk drives, as the recording density (i.e. bits-per-inch and/or tracks-per-inch) is increased, maintaining transducer head tolerances has become a challenge. Variance in the relative head performance distribution increases with increasing data density. In conventional disk drives, the drive yield and capacity suffers as a result of head performance variations in disk drives.

One method of increasing the data storage capacity of a disk drive includes increasing the areal density of the data stored on the media surfaces (bits/sq. in. -- BPSI). Areal density is the track density which is the number of tracks per radial inch (TPI) that can be packed onto the media/recording surface, multiplied by the linear density (BPI) which is the number of bits of data that can be stored per linear inch.

Conventional processes for qualifying disk drives scrap a disk drive when the measured disk capacity of the disk drive is less than a target disk capacity. Conventionally, each recording surface is formatted to store the same amount of data as every other recording surface. Thus, a recording surface that has a low error rate is formatted to the same TPI and BPI levels, as a recording surface having a high error rate, even though it can store more data. However, by adopting a single TPI and BPI level for every recording surface, conventional processes fail to account for the differences in sensitivity and accuracy of the paired head and recording surface, which results in less data storage and more waste of space on each recording surface. This also results in lower overall yields of disk drives because if even a few of the recording surfaces do not meet their targeted capacity, the sum of the surface capacities of all the media surfaces will be less than the target capacity, causing the entire disk drive to fail.

U.S. Patent Nos. 6,091,559 and 5,596,458 provide for recording at different BPI on different recording surfaces, however, such methods do not take into consideration multiple constraints, including head performance across the stroke per disk surface affecting disk drive capacity, disk drive performance requirements (e.g., throughput) and manufacturing requirements (e.g., test time). Zone frequencies are selected based on measurement of a single metric on one head.

There is, therefore, a need for a method of storing data in a disk drive which improves disk drive yield while meeting the desired target drive capacity or increasing the drive capacity while meeting a desired drive yield by taking advantage of the head performance variation.

Summary of the Invention

The present invention satisfies these needs. According to one embodiment of the present invention, a population of disk drives is selected, and head performance measurements are taken for each selected media surface location at different frequencies. Performance distributions are obtained from the measured data, and a format optimizer uses the distributions to obtain a design of different frequencies across the media surface zones, and determine head allocation. Once the different frequencies for the zones have been determined, then in each disk drive, the heads are assigned to the predetermined frequencies optimized for. As such, the present invention allows maintaining consistent performance (both sequential and random throughput) across a population of disk drives, and reduced test time. This is accomplished by determining head performance and design of format at development/design time, and assignment of heads to different frequencies at manufacturing time. Therefore, predetermined design of formats is performed off-line, and then marries to a manufacturing test process for assignment of heads to different frequencies.

1 In one example, the density/format for each recording surface zone and
2 the number of heads allocated to each density, are preselected at design time,
3 and at manufacturing time heads are assigned to higher/lower density formats.
4 Unlike conventional methods, head allocation and assignment is per head per
5 zone, taking into consideration head performance variation across zones. As
6 such, if a first head that performs well at ID but poorly at OD, and a second head
7 has reverse performance, that performance is traded off wherein the first head is
8 assigned to high density at ID and at low density at OD, and the second head in
9 the opposite fashion. In the per zone variable BPI for improving capacity
10 according to the present invention, several manufacturing and customer
11 constraints are taken into consideration. Performance of each head across the
12 stroke, as well performance variation from one head to another, is utilized in
13 designing the density format and assignments of heads to the density formats.
14

15 The present invention provides a variable BPI storage format as a function
16 of storage zones in storage devices, such as disk drives, based on transducer
17 head performance variations between different heads in a set of disk drives. The
18 present invention provides a method of defining such a storage format in multiple
19 data storage devices, each data storage device having a plurality of storage
20 media and a plurality of corresponding data transducer heads, each transducer
21 head for recording on and playback of information from a corresponding storage
22 medium in multiple zones, wherein each zone includes a plurality of concentric
23 tracks for recording on and playback of information. The method includes the
24 steps of: selecting a plurality of said data storage devices; for each selected data
25 storage device, measuring a record/playback performance capability of each
26 head at one or more read/write frequencies per zone; based on said performance
27 capability measurements, generating storage density distributions corresponding
28 to at least a number of the heads in said selected data storage devices; selecting
29 a group of read/write frequencies for said multiple data storage devices, two or
30 more frequencies for each zone, based on said storage density distributions; and

thereafter, during manufacturing, assigning one of said read/write frequencies to each head based on performance capability of that head per storage device.

Brief Description of the Drawings

These and other features, aspects and advantages of the present invention will become understood with reference to the following description, appended claims and accompanying figures where:

FIG. 1A shows an example partial schematic diagram of a disk drive with an example data storage format according to the present invention;

FIG. 1B shows another example schematic of the disk drive of FIG. 1A illustrating disk drive electronics;

FIG. 1C shows an example surface format for data storage according to the present invention;

FIG. 1D shows an example diagram representing the general zone layout of a disk drive with N disks and $2N$ heads, depicting different heads in a section of a zone on different disk surfaces;

FIG. 1E shows another example of capacity zone layout on a surface a disk;

FIG. 1F shows example of a series of radial zones on a disk surface, wherein each zone includes multiple virtual cylinders;

FIG. 1G shows an example representative data track layout for each of several virtual cylinders in a zone on different disk surfaces with corresponding heads;

FIG. 1H shows another example servo track and data track layout for a zone on different disk surfaces with corresponding heads, wherein the number of servo tracks and data tracks in different virtual cylinders of a zone on different disk surfaces are the same;

FIG. 1I shows another example layout wherein the servo and data track layout varies from zone to zone on a disk surface;

FIG. 2A shows an example flow/functional diagram of embodiment of steps of generating the layout of FIG. 1I according to the present invention;

FIG. 2B shows a graph of playback error measurement for a head at a zone at different recording frequencies;

FIG. 2C shows an example joint BPI distribution plot;

FIG. 2D shows an example histogram of the frequency capabilities of the heads in a set of disk drives at a zone at a fixed target error rate;

FIG. 3 shows an example flowchart of an embodiment of steps of variable zoning data collection process of FIG. 2A;

FIG. 4 shows an example flowchart of an embodiment of steps of vertical zoning post-measurement processing and per zone BPI distribution extraction process of FIG. 2A;

FIG. 5 shows an example flowchart of an embodiment of steps of vertical zone assignment process of FIG. 2A; and

FIG. 6 shows an example flowchart of an embodiment of steps of format generation and optimization interaction process of FIG. 2A.

Detailed Description of the Invention

Data storage devices used to store data for computer systems include, for example, hard disk drives, floppy disk drives, tape drives, optical and magneto-optical drives, and compact disk drives. Although the present invention is illustrated by way of an exemplary magnetic hard disk drive 100, the invention can be used in other storage media and drives, including non-magnetic storage media, as apparent to one of ordinary skill in the art and without deviating from the scope of the present invention.

Referring to FIGs. 1A-C, an exemplary hard disk drive 100 is diagrammatically depicted for storing user data and/or operating instructions for a computer system 54. The hard disk drive 100 comprises an electro-mechanical head-disk assembly 10 shown in FIG. 1A as including one or more rotating data storage disks 12 mounted in a stacked, spaced-apart relationship upon a rotating spindle 13. The spindle 13 is rotated by a spindle motor 14 at a predetermined angular velocity.

1
2 Each disk 12 defines at least one media surface 23, an usually two media
3 surface 23 on opposing side of each disk 12. Each media surface 23 is coated is
4 coated with magnetic or other media for recording data. The spindle drive motor
5 14 turns the spindle 13 in order to move the disks 12 past magnetic transducer
6 heads 16 suspended by suspension arms 17 over each media surface 23.
7 Generally, each magnetic head 16 is attached to the suspension arm 17 by a
8 head gimbal assembly (not shown) that enables magnetic head 16 to swivel to
9 conform to the media surfaces on the disks 12. The suspension arms 17 extend
10 radially from a rotary voice coil actuator (not shown). An actuator motor 54
11 rotates the actuator and head arms and thereby positions the magnetic heads 16
12 over the appropriate areas of the media surfaces 23 in order to locate and read
13 or write data from or to the storage surfaces 23. Because the disks 12 rotate at
14 relatively high speed, the magnetic heads 16 ride over the media surface 23 on a
15 cushion of air (air bearing). Each magnetic head 16 comprises a read element
16 (not shown) for reading magnetic data on magnetic storage media surfaces 23
17 and a write element (not shown) for writing data on the media surfaces 23. Most
18 preferably, although not necessarily, the write element is inductive and has an
19 electrical writing width which is wider than an electrical reading width of the read
20 element, which is preferably of magnetoresistive or giant magnetoresistive
21 material.

22
23 Referring to FIG. 1C, each media surface 23 is divided into a plurality of
24 concentric circular tracks 30 that each have individually addressable portions 35,
25 such as sectors, in which data is stored in the form of magnetic bits. The data
26 sectors 35 are separated by embedded narrow servo sectors or spokes 25 which
27 include a series of phase-coherent digital fields followed by a series of constant
28 frequency servo bursts. The servo bursts are radially offset and
29 circumferentially sequential, and are provided in sufficient numbers such that
30 fractional amplitude signals picked up by the read element from portions of at
31 least two bursts passing under the read element enable the controller 57 to

1 determine and maintain proper head position relative to a data track 30. One
2 example of a servo burst pattern for use with an inductive write
3 element/magneto-resistive read element head 16 is provided by commonly
4 assigned U.S. Patent No 5,587,850, entitled: "Data Track Pattern Including
5 Embedded Servo Sectors for Magneto-Resistive Read/Inductive Write Head
6 Structure for a Disk Drive", incorporated herein by reference.

7
8 The drive controller 57 controls operation of the pairs of magnetic heads
9 16 and media surfaces 23 to read and write data onto each media surface 23.
10 The drive controller 57 preferably comprises an application specific integrated
11 circuits chip which is connected by a printed circuit board 50 with other chips,
12 such as a read/write channel chip 51, a motors drive chip 53, and a cache buffer
13 chip 55, into an electronic circuit as shown in FIG. 1B. The controller 57
14 preferably includes an interface 59 which connects to the host computer 54 via a
15 known bus structure 52, such as ATA or SCSI.

16
17 The controller 57 executes embedded or system software comprising
18 programming code that monitors and operates the controller system and driver
19 100. During a read or data retrieval operation, the computer system 54
20 determined the "address" where the data is located on the disk drive 100, i.e.,
21 magnetic head number, the track 30, and the relevant portion(s) 35 of the track
22 30. This data is transferred to the drive controller 57 which maps the address to
23 the physical location in the drive, and in response to reading the servo
24 information in the servo sectors, operates the actuator motor 54 and suspension
25 arm 17 to position a magnetic head 16 over the corresponding track 30. As the
26 media surface 23 rotates, the magnetic head 16 reads the servo information
27 embedded in each spoke 25 and also reads an address of each portion 35 in the
28 track 30. When the identified portion 35 appears under the magnetic head 16,
29 the entire contents of the portion 35 containing the desired data are read. In
30 reading data from the media surface 23, the read element (not shown) senses a
31 variation in an electrical current flowing through a magnetoresistive sensor of the

1 read element (not shown) when it passes over an area of flux reversal on the
 2 surface 23 of the media. The flux reversals are transformed into recovered data
 3 by the read/write channel chip 51 in accordance with a channel algorithm such as
 4 partial response, maximum likelihood (PRML). The recovered data is then read
 5 into the cache memory chip 55 of the disk drive 100 from whence it is transferred
 6 to the computer system 54. The read/write channel 51 most preferably includes
 7 a quality monitor function which enables measurement of the quality of recovered
 8 data and thereby provides an indication of data error rate. One channel
 9 implementation which employs channel error metrics is described in commonly
 10 assigned U.S. Patent No., 5,521,945 to Knudson, entitled: "Reduced Complexity
 11 EPR4 Post-Processor for Sampled Data Detection", incorporated herein by
 12 reference. The indication of recovered data error is used in order to select linear
 13 data density, track density and/or error correction code levels, in accordance with
 14 principles of the present invention, as more fully explained hereinbelow.

15
 16 Writing or storing data on the media surface 23 is the reverse of the
 17 process for reading data. During a write operation, the host computer system 54
 18 remembers the addresses for each file on the media surface 23 and which
 19 portions 35 are available for new data. The drive controller 57 operates the
 20 actuator motor 54 in response to the servo information read back from the
 21 embedded servo sector 25 in order to position a magnetic Head1, settles the
 22 head 16 into a writing position, and waits for the appropriate portions 35 to rotate
 23 under the head 16 to perform the actual writing of data. To write data on the
 24 media surface 23, an electrical current is passed through a write coil in the
 25 inductive write element (not shown) of the head 16 to create a magnetic field
 26 across a magnetic gap in a pair of write poles that magnetizes the magnetic
 27 storage media coating the media surface 23 under the head 16. When the track
 28 30 is full, the drive controller 57 moves the magnetic head 16 to the next
 29 available track 30 with sufficient contiguous space for writing of data. If still more
 30 track capacity is required, another head 16 is used to write data to a portion 35 of
 31 another track 30 on another media surface 23.

1
2 In one aspect, the present invention increases the data storage capacity
3 and yield of data storage devices having a plurality of media surfaces 23, such as
4 hard disk drive 100 including disks 12 covered with magnetic media.

5
6 Overview of general method vertical zoning

7 In every disk drive, there is a distribution associated with head/media pair
8 performance in that disk drive. The present invention takes advantage of that
9 distribution to determine different linear density recording frequency assignment
10 for heads, and optionally track allocation. According to one embodiment of the
11 present invention, a set of disk drives is selected, and head performance
12 measurements are taken for each selected media surface location in the disk
13 drives at different frequencies.

14
15 Empirical frequency capability histograms are extracted at a given known
16 target performance metric from measurement data. Probability cumulative
17 distribution functions (such as joint probability distributions) are estimated from
18 the histograms and fed into a format optimizer to obtain and design (vertically
19 zoned) frequency format profiles (i.e., across the stroke and media surface
20 zones) as well as optimal number of head allocations to frequencies. Once
21 frequency format profiles and optimal number of head allocations are designed
22 and pre-determined, during a test process, every head at every zone is assigned
23 to one of the multiple pre-determined frequencies based on the head's
24 performance capability.

25
26 As such, the present invention allows maintaining consistent performance
27 (sequential/random throughput) across several of disk drives, without introducing
28 significant additional test time. This is accomplished by determining head
29 performance and design of format at development/design time, and assignment
30 of heads to different frequencies at manufacturing time. Therefore, the
31 predetermined design of frequency format profiles and (optimal) number of head

allocations are performed off-line while the assignment of heads to different frequencies is performed during the test process such as during manufacturing.

Unlike conventional methods, in the present invention head allocation and assignment is per head per zone, taking into consideration head performance variation across zones (i.e. across the stroke). As such, during head frequency assignment, if a first head performs well at ID but poorly at OD, and a second head has the opposite performance, the performance variation between the heads is traded off such that the first head is assigned to high density (frequency) at ID and at low density at OD, and the second head is assigned to low density at ID and high density at OD. In a method of per zone variable bits-per-inch (BPI or linear density) for improving capacity according to the present invention, several manufacturing and customer constraints are taken into consideration. And, performance of each head across the stroke, as well performance variation from one head to another, is utilized in designing the density format and assignments of heads to the density formats.

Referring back to FIG. 1A, an example of density layout according to an embodiment of the present invention is shown. In one aspect, the present invention provides a variable BPI layout as a function of zones on each disk surface 23 based on e.g. two data recording formats (i.e., low density and high density) that utilize: (1) head performance variation from one head to the next in the disk drive and (2) the performance (variation) of a given head across the stroke on a disk surface. Further, the present invention provides a method of generating said layout.

In this example, each zone comprises a group of tracks laid out in zones 60 between one radius and another radius on the disk surface 23, wherein the zone layout for the multiple disk surfaces in each disk drive 100 are the same. A disk drive 100 includes N disks 12 (Disk1 through DiskN), *each disk having a Surface1 and opposing Surface2*, wherein each disk surface has M zones

1 (Zone1 through ZoneM) across the actuator stroke, and one head per disk
 2 surface. For each disk surface, Zone1 is in ID, ZoneM is in OD, wherein the
 3 radial boundaries of Zone1 of Surface1 of Disk1 are the same as boundaries of
 4 Zone1 of Surface2 of Disk1 *and so on*. Similarly, the radial boundaries of ZoneM
 5 on Surface1 of Disk1 are the same as radial boundaries of ZoneM on Surface2 of
 6 Disk 1, and so on. However, different zones across the stroke on each disk
 7 surface need not necessarily have the same number of tracks or TPI (e.g., Zone1
 8 and ZoneM on the same surface do not necessarily have the same number of
 9 tracks). For example, Zone1 *on Surface1 of Disk1* (i.e., Head1) has same
 10 number of tracks and physical zone boundaries as Zone1 *on Surface1 of DiskN*
 11 (Head 2xN), etc. And, ZoneM *on Surface1 of Disk1* (Head1) has the same
 12 number of tracks and physical zone boundary as ZoneM *on Surface1 of DiskN*
 13 (Head2N). However, the number of tracks in Zone1 and ZoneM can be different.
 14 The physical zone boundaries vertically align on the disks in each disk drive,
 15 forming virtual cylinders 39 (VC). In this example, there are n virtual cylinders
 16 39, VC1 through VCn. Within a virtual cylinder, different heads may read/write at
 17 different frequencies (e.g., variable BPI), hence the concept of vertical zoning.
 18

19 The level of track density (TPI) can be one of fixed number of preselected
 20 levels or can be derived from an algorithm that is based on the location of a
 21 portion 35 of the media surface 23. Embedded servo sectors 25 are initially
 22 written on a media surface 23 during a factory servo-writing process at a servo
 23 track density that can be higher than the data track density, as illustrated in FIG.
 24 1C. Servo bursts within each servo sector 25 are provided in such number and
 25 placement to enable accurate positioning of the magnetic head 16 in a full range
 26 of positions across the media surface 23, given the particular effective width and
 27 characteristics of the read element of a particular head (the read element width
 28 typically being narrower than the writer carry out the head positioning method,
 29 information in the embedded servo sector 25 is read by the magnetic head 16
 30 and passed to the drive controller 57 which directs the actuator motor 20 to
 31 readjust the position the suspension arm 16. In the example shown in FIG. 1C,

1 the servo track density is about 150% of the maximum possible data track
2 density. In FIG. 1C five servo tracks 37 (e.g., Sa, Sb, Sc, Sd and Se) are shown
3 in relation to three data tracks Tk1, Tk2 and Tk3. Servo track density is
4 determined by determining the max. read and min. write width of a population of
5 magnetic heads 16. After writing the servo wedges 25 at the servo track pitch,
6 the actual data track 30 can be written at any disk radial position between the
7 servo tracks 37. Additional tests, can be performed to determine the optimum
8 data track density of the media surface 23. Each servo track comprises radially
9 similarly situated servo information in servo wedges 25 (e.g., the set of servo
10 information Se at essentially same radial distance from the disk center form a
11 servo track circumferentially, set of servo information Se at essentially same
12 radial distance from the disk center form another servo track circumferentially,
13 etc.)
14

15 FIG. 1D shows an example diagram representing the general zone layout
16 of a disk drive with N disks and 2N heads, depicting different heads in a section
17 Zone1 on different disks. FIG. 1E shows another example of capacity zone
18 layout on a surface a disk. FIG. 1F shows example of a series of radial zones,
19 Zone1 through ZoneM, on a disk surface, wherein each zone includes multiple
20 virtual cylinders. FIG. 1G shows an example representative data track layout for
21 each of several virtual cylinders in a zone (e.g., Zone1), on different disk surfaces
22 with corresponding heads. FIG. 1H shows another example servo track 37 and
23 data track 35 layout for a zone 60 on different disk surfaces 23 with
24 corresponding heads, wherein the number of servo tracks and data tracks in
25 different virtual cylinders 39 of a zone (e.g., Zone1) on different disk surfaces 23
26 are the same. And, FIG. 1I shows another example layout wherein the servo and
27 data track layout varies from zone to zone 60 on a disk surface 23. In all of the
28 above examples of vertical zoning layout according to the present invention,
29 within a virtual cylinder 39, different heads on different surfaces may read/write at
30 different linear frequencies on the data tracks (e.g., variable BPI).
31

Overview of Format Optimization

In one embodiment, a vertical zoning method according to the present invention includes designing/optimizing (selecting) for two or more recording frequency profiles (i.e., per zone) for a sample number of disk drives (e.g., performed off-line during disk drive development/design phase). Then for a population of disk drives, in each disk drive, each head is assigned to one of the predetermined frequencies for a given zone (e.g., during disk drive manufacturing phase). The assignment step includes assigning a predetermined read/write frequency (BPI) to each head based on a known number of head allocations and the head's performance capability. A head assigned to a higher frequency/density (HD) records more bits on a track, and a head assigned to a lower frequency/density (LD) records less bits on a track.

Referring to the example in FIG. 1A, if the tested performance of Head1 at Zone1 on Surface1 of Disk1 at a given frequency (after full drive read/write and servo calibration/optimization) is better than a desired target performance metric, then that (strong) head, Head1, is considered to have some margin for storing more information than it was originally accounted for. Thus, the designed recording frequency can be increased at Zone1 on Surface1 of Disk1 for Head1 so as to ensure its performance does not fall below the desired target performance metric. If the tested performance of Head2 at Zone1 on Surface2 of Disk1 at that same frequency (after full drive read/write and servo calibration/optimization), is worse than a desired target performance metric, then that (weak) head, Head2, can be compensated for by relaxing the frequency at which Head2 operates, so as to ensure the target performance metric is met. Performing the above tradeoff between the heads for all zones, without loss of overall capacity, provides resulting frequency profiles (i.e. across the stroke) comprising vertically zoned frequency format profiles.

As the above example shows, by compensating for weak Head2, rather than failing the disk drive due to the weak Head2, vertical zoning improves the

1 disk drive yield. Without application of vertical zoning such a disk drive would not
2 have passed the test limits, and hence would have failed. Furthermore, the
3 format optimizer uses the estimates of performance (i.e., read/write frequency
4 capability) cumulative distribution function at every zone and target performance
5 metric, to design a group of read/write frequency format profiles for weak and
6 strong heads within a given disk drive. The format optimizer also determines the
7 optimal number of, for example, weak versus strong heads.

8
9 The format optimizer does not determine which specific head is actually at
10 the lower or higher frequency, but only provides a breakdown of the number of
11 heads at lower frequency and the number of heads at the higher frequency. That
12 breakdown is fixed, performed off-line, and is used during the head assignment
13 process. Then in the assignment process (e.g., during manufacturing test
14 process), out of $2 \times N$ heads in a disk drive with N disks, the number of heads that
15 have to be assigned to each predetermined frequency/format is also
16 predetermined (e.g., number heads to assign to low frequency and number of
17 heads to assign to high frequency).

18
19 As such, the heads within a set of disk drives are allocated to the
20 predetermined group of read/write frequencies as part of the optimization
21 process to meet capacity and yield requirement for the disk drives. The
22 allocation process allocates a number of heads in a disk drive to one of the
23 predetermined/designed frequencies, however specific assignment of a particular
24 head to a particular frequency is performed as part of the assignment process
25 thereafter. In one example, in a 2 read/write frequency design (high density and
26 low density) for a set of disk drives each with 8 heads, in each disk drive for
27 Zone1 on all disk surfaces, any 3 heads of the 8 heads are allocated to lower
28 frequency and any 5 heads of the 8 heads are allocated to higher frequency in
29 the allocation process based on the performance measurements of all the heads
30 in the set of disk drives. Thereafter, the specific assignment of each particular
31 head to a particular predetermined frequency is performed as part of the

1 assignment process. For example, in a first disk drive heads 1, 3, 4 are
2 assigned to low frequency, and heads 2, 5, 6, 7, 8 are assigned to high
3 frequency, whereas in a second disk drive heads 2, 3, 8 are assigned to low
4 frequency, and heads 1, 4, 5, 6, 7 are assigned to high frequency, and so on,
5 wherein the specific assignments depend on specific capability of the heads in
6 each disk drive.

7
8 The optimal number of heads per frequency (i.e., head allocation) is
9 determined at the same time that the group of read/write frequencies are
10 designed/selected by the format optimizer, by solving a joint constrained
11 optimization problem. For example, in the 8-head disk drive above, for the case
12 of two frequencies (high frequency freq1 and low frequency freq2) at a ratio to a
13 frequency freq, in each vertical zone, allocating 2 heads to freq1 and allocating 6
14 heads to freq2, provides a first disk drive capacity. Changing said ratio of the
15 frequencies and the number of heads allocated to each frequency, provides a
16 different capacity for that disk drive. As such, the disk drive capacity is a function
17 of the number of heads multiplied by the frequency allocated to each head per
18 zone. For example, if a nominal surface capacity is 1 unit, and if $\text{freq1} = \frac{4}{3} \times \text{freq}$
19 and $\text{freq2} = \frac{2}{3} \times \text{freq}$, then one head can be at freq1 for every one head at
20 freq2, whereby the average surface capacity is 1 unit. Using the head
21 performance distributions (i.e., head read/write frequency capability distributions
22 at the target performance metric for every zone), the number of heads, the format
23 of the virtual cylinder, and a desired capacity, the format optimizer determines
24 the frequency for each zone in each virtual cylinder and the number of heads in
25 each disk drive allocated to each frequency, in order to achieve that desired
26 capacity. Thereafter, in the assignment process (e.g., as part of a testing of each
27 disk drive), each specific head in a population of disk drives is assigned to one of
28 the predetermined frequencies based on the allocation criteria and specific head
29 performance.

For an example 4-head disk drive, the format optimizer considers 3 heads at freq1 and 1 head at freq2, then 2 heads at freq1 and 2 heads at freq2, and then 1 head at freq1 and 3 heads at freq2. And in each case, using the estimated head performance cumulative distribution functions determines the disk drive yield. The head performance distributions (e.g., BPI distributions) represent percentages of the heads in the disk drives than can operate at different frequency densities. This allows the format optimizer to determine the yield and capacity. In the description of the example embodiment herein, head performance distribution, such as a BPI distribution, represents head frequency capability (probability) cumulative distribution at a target performance metric.

In one version of the optimization process, disk drive yield is maximized while meeting a constraint on capacity. In another version, the capacity is maximized while meeting a constraint on disk drive yield. In the former case, the format optimizer uses a format where the higher frequency is freq1 and the lower frequency is freq2. In the example 4-head disk drive, allocating 2 heads to freq1 and 2 heads to freq2, provides a surface capacity of 1 unit, and capacity of 4 units for the disk drive. If 3 heads are allocated to the higher freq1 and 1 head to the lower frequency freq2, a higher capacity (i.e. 4 and 2/3) is achieved for the disk drive. In that case, the format optimizer lowers the zone recording frequencies to meet that constraint of capacity of 1 unit per surface. As such, for 2 heads at freq1 and 2 heads at freq2, the format optimizer manipulates the difference of those frequencies such that surface capacity always reaches 1 unit, but maximizes yield whereby a maximum number of disk drives qualify and fewest number of disk drives fail to reach required capacity.

As such, according to one embodiment of the present invention, a vertical zoning approach for variable BPI design includes use of an off-line predetermined per zone design of formats based on disk drive data collection and (joint) BPI distribution extraction methods. In one version, a fixed predetermined zone boundary layout is used to design multiple frequency BPI

1 formats based on representative or actual BPI distributions at one or more
2 desired target metrics (such as off-track error rate), wherein the BPI distributions
3 are extracted from a finite pre-selected set of disk drives.

4
5 The collected data is used to extract said BPI distributions for the heads at
6 every (pre-selected) zone, and the per zone design of low/high density formats
7 for the heads is performed offline. The format optimizer solves a constrained
8 joint optimization process off-line to obtain said format designs, using well-
9 known constrained optimization routines. Using joint BPI distributions allows
10 consideration of potential correlation of BPI capability of heads across the stroke
11 as well as individual contribution of each head to the overall drive capacity (or
12 areal density) and yield.

13
14 The off-line design of formats allows consideration of other potential
15 constraints that may arise, as additional constraints within the optimizer, and
16 hence solved by the optimizer. For example, as more information is obtained in
17 quantifying the thermal stability constraints of the recording media (which in turn
18 places an upper bound of linear density for the heads) the off-line design
19 provides the ability of not exceeding those limits. If there are data rate limitations
20 in either the write process capability or ASIC component capability, such
21 constraints may be cast within the joint constrained optimizer to ensure said
22 limits are not exceeded.

23 24 Overview of Measurement Process

25 In one implementation of the method of the present invention, a
26 measurement procedure is used to collect data, such that after processing of the
27 collected data, one-dimensional (1-D), two dimensional (2-D) as well as three
28 dimensional (3-D) joint BPI (probability) distributions at a desired read/write
29 target error rate (or any other choice of metric) can be extracted. Data is
30 collected based on head capability measurements taken at different radial
31 positions of the disk. The collected data is used to extract 1-D, 2-D and 3-D

empirical distributions at a target choice of performance metric. The dimensions are dimensions of the distribution, and the distributions represent capability of each head at different radial positions. For example, several disk drives which collectively include 1000 heads are selected for measurement. In a measurement process, record/playback error rate measurements of the 1000 heads from Zone1 to Zone24 of disk surfaces at different frequencies are obtained. Thereafter, in post-measurement processing: (a) the BPI capability of every head at a fixed target metric at e.g. Zone1 is determined in order to obtain a 1-D BPI distribution, (b) the BPI capability of the head at a fixed target metric at e.g. Zone1 and Zone5 is determined in order to obtain a 2-D BPI joint distribution, and (c) the BPI capability of the head at a fixed target metric at e.g. Zone1, Zone5 and Zone20 is determined in order to obtain a 3-D BPI joint distribution.

The BPI distributions are then used as input to the format optimizer to solve three constrained optimization problems to provide head frequency per zone allocations, wherein: (1) one problem maximizes disk drive yield while preserving the same drive capacity, (2) another maximizes the disk drive capacity while preserving the same drive yield and, and (3) another maximizes disk drive yield while ensuring a desired target drive capacity is met at a fixed target track-per-inch (TPI). Additionally, customer related or application specific integrated circuit (ASIC) data rate (limitation) constraints are also utilized. The format optimizer is capable of solving any one of the above-mentioned three problems, wherein one problem can take priority over another depending on the process phase. For example, at earlier development phase of a program where the disk drive components are not matured yet, meeting the drive capacity may be a challenge. In that case, the format optimizer can be used to design variable BPI format profiles by solving the second problem above. As the disk drive components mature such that meeting the drive capacity becomes easier and meeting the drive yield becomes more important, the first may be considered instead. Thereafter, as part of a test process, an algorithm is used to ensure

1 appropriate head assignment to high/low density (pre-specified) formats per head
2 and per zone or across the head strokes, based on head allocation breakdown of
3 the format optimizer.

4
5 Disk drive yield is improved while meeting desired target drive capacity by
6 allowing a frequency format layout (e.g., high and low frequency) with a
7 predetermined number of high and low performing head allocations. Utilizing
8 realistic constraints such as ASIC data rate limitations, the same fixed target TPI
9 is maintained by increasing the average target BPI across the head stroke on a
10 disk surface to achieve the desired disk drive data storage capacity. As such,
11 head performance variation from one head to the next head in the disk drive (and
12 across the stroke across a disk surface) is utilized to allow increasing the areal
13 density of the stored information while preserving the same overall disk drive
14 yield. In one example, a vertical zoning layout method according to the present
15 invention utilizes several design constraints to improve the drive yield using
16 variable low/high BPI design with a fixed predetermined number of head
17 allocations as a function of zones while meeting the target capacity at a fixed
18 target TPI. Head performance variation or correlation across the stroke is also
19 utilized.

20
21 Further, the method of present invention takes into consideration the
22 difference in storage capacity of two or more zones on a disk surface, as it
23 affects overall disk drive capacity. The disk drive capacity is defined as a
24 weighted combination of zone capacities across the stroke on each disk surface.
25 A correlation in the head performance statistics is extracted from one head to
26 another head, and for every given head considered in a set of disks drives across
27 the head stroke on each disk surface.

28
29 The joint constrained optimization process determines a per zone target
30 low/high data density format/layout. The optimization process takes into account
31 constraints including customer related requirements such as the requirement of a

1 minimum logical block count (LBA), monotonic data rate, and maximum data rate
2 requirements at the outer zone areas which can be formulated into (additional)
3 constraints. Head allocation and assignment according to the present invention
4 improves manufacturing yield and provides a disk drive with minimal
5 performance degradation (i.e., sequential or random throughput as well as test
6 process time).

7 8 Example Implementation

9 FIG. 2A shows an example function and flow diagram of an example
10 implementation of the above-described method according to the present
11 invention for generating optimal data density format/layout shown by example in
12 FIG. 1A. The example method in FIG. 2A includes: a data
13 collection/measurement process (block) 62, a data post-measurement-process
14 (block) 64, format optimizer process (block) 66, format generator process and
15 head assignment process (block) 68, example embodiments of which are
16 described below.

17 18 Data Collection/Measurement process

19 In one embodiment, the measurement block 62 implements a
20 measurement procedure including the steps of:

- 21 1. Creating several different predetermined linear density format profiles
22 comprising a profile of different frequencies per zone across the actuator stroke,
23 such as e.g. a first profile including freq1_1 for Zone1, freq1_2 for to Zone 2, ...,
24 freq1_M for ZoneM; and second profile including freq2_1 for Zone1, freq2_2 for
25 Zone 2, ..., freq2_M for ZoneM, etc., to be loaded on a representative number of
26 disk drives selected for the measurement process (or if possible on all of the
27 available built drives for that build);
- 28 2. Loading a frequency format profile;
- 29 3. Performing read/write and servo optimization and calibration;
- 30 4. Taking head performance measurements including e.g. (off-track)
31 mean square error (MSE) or quality metric (QM) and/or symbol error rate (SER)

1 measurements at pre-selected frequencies for preferably all available zones, and
2 saving the data; and

3 5. Repeating steps 2-4 above for all the remaining frequency format
4 profiles.

5
6 The above steps are performed for the selected disk drives in the
7 measurement process.

8
9 As such density is selected and data is recorded on a portion of the media
10 surface 23 at the selected density by positioning a magnetic head 16 abutting the
11 portion 35 of the media surface 23, and sending the appropriate signals to the
12 write element (not shown) of the magnetic head 16. Typically, a sample of data
13 such that a significant number of errors are detected (e.g., 10 errors per error
14 rate measurement), is recorded on the media surface 23 to obtain a statistically
15 representative sampling of the error rate for the portion 35 of the media surface
16 23. Thereafter, the recorded data is read by the read element (not shown) of the
17 magnetic head 16, and the data read is stored by the computer system 54 for
18 evaluation. An error rate of the recorded data is measured or compiled by
19 comparing the actual written data with the read data, element by element.
20 Suitable methods of determining the error rate include actual bit error
21 measurement in which a bit of data read from the media surface 23 is compared
22 with the correct bit, or a correct bit stream is compared with a measured bit
23 stream. An alternative method uses the mean square error metric method in
24 which a waveform read from the media surface 23 is compared with an ideal
25 waveform to provide an error signal that is squared and summed to form the
26 error metric.

27
28 In this description, a component distribution is defined to be a (random)
29 variation (i.e., tolerance) of a pre-specified (target) nominal component
30 parameter such as a head write/read width, and the term distribution is defined
31 as the probability distribution function (PDF). During early product development

1 process, when the head performance distributions are wide and unreliable, data
2 from a matured set of disk drives is used for extracting reference (joint) BPI
3 distributions at a target metric (e.g., off/on track error rate or mean square error).
4 Later in the process, when the amount of head performance variations from one
5 phase to the next in the distribution is expected to be minimal, new sets of
6 measurement data are collected using a selected plurality/population of disk
7 drives at their more matured stages.

8
9 Thus, a number of BPI formats including the nominal target format are
10 selected. Then, off or on track error rate or MSE measurements at different pre-
11 selected locations of the disk surfaces, e.g., outer, middle and inner zone are
12 taken (in one example scenario described further below, the choice is limited to
13 said three zones, to reduce the time for performing measurement). However,
14 preferably measurements over multiple zones can be performed and other
15 measurements such as off-track measurements (e.g., 747 measurements) can
16 also be taken. The nominal formats are generated from the data.

17
18 Two or more different linear density format profiles can be loaded at a
19 time. In one example, two variable BPI format per zone design (low/high density
20 format profiles) can be created for the purpose of measurement data collection
21 during every build. In this way, more statistical data can be collected from more
22 disk drives, however, there will be only two frequency samples per zone available
23 for data post-measurement processing.

24 25 Raw Data post-measurement-process

26 In the above steps, measurements (e.g. either MSE or SER) for every
27 zone are taken at a finite number of frequency samples. In post-measurement
28 processing (post-processing) block 64, using the available performance metric,
29 measurements are used to calculate each head's frequency performance (e.g.,
30 kilo flux per inch (kFCI) or kilo bits per inch (kBPI)) at a given target performance

metric. The performance of every head at every zone is determined as a function of said read/write frequency profiles used for the measurements.

For example, if 6 different frequency profiles are used, then for every head per zone, the measurement process 62 provides measured data as a function of 6 frequency samples at a target metric. In the post-measurement process 64, all the measured data is sorted and performance of every head at every zone at the 6 different frequency samples is extracted to generate frequency capability histograms at a target performance metric (e.g. error rate). Referring to FIG. 2B, the samples can be depicted in a two dimensional graph wherein the x-axis (horizontal) is frequency (e.g., frequencies 1 through 6, kBPI at outer diameter OD), and the y-axis (vertical) is error rate measurement in log scale for Head1 at zone 1 for each of said 6 frequencies (log SER) (in FIG. 2B, each sample data 70 is depicted as a "+"). The error rate measurement can vary e.g. from $1e^{-4}$ (i.e., 1×10^{-4}) to $1e^{-7}$ (i.e., 1×10^{-7}) as a function of the 6 frequencies, wherein the error rate increases as the read/write frequency (density) increases.

To determine frequency capability of e.g. Head1 at Zone1 at a target error rate of $1e^{-6}$ (i.e., 1×10^{-6}), a curve is fit (e.g., using known curve-fitting techniques such as least squares polynomial fit) to the 6 samples, to determine by interpolation the frequency value that gives rise to that target error rate (in FIG. 2B, each curve fit point 72 is depicted by a "o"). If the target error rate is at $1e^{-8}$ (i.e., 1×10^{-8}) then the frequency value that gives rise to that target error rate is determined by extrapolation (in FIG. 2b, the projected or extrapolated frequency value 74 is shown as a diamond shape). The process for that target error rate is performed for Zone1 for all the heads in the selected disk drives used in the measurement process 62, to create a histogram (FIG. 2D) of the frequency capabilities of all the heads in the disk drives at Zone1 at that fixed target error rate. The process is the same for all zones. As such, using every available head considered in the disk drives under measurement, BPI histograms can be extracted at a given target performance metric per zone.

1
2 FIG. 2B shows an example curve of error rate of performance (SER) as a
3 function of BPI (e.g., SER at 6 different BPI/frequency samples) for a head
4 located at the outer diameter (OD) of the disk. Also shown is extracted
5 BPI/frequency capability value of that head at a zone (e.g., OD) for the specified
6 target error rate, using interpolation/extrapolation (i.e., if the specified desired
7 target error rate is outside the performance range, extrapolation or interpolation,
8 such as polynomial fit, is used as necessary). The amount of BPI gain, or margin
9 relative to the nominal BPI setting, is also specified and marked.

10
11 The above process is performed for all the heads considered in the
12 measurement procedure, and a BPI/frequency capability of all heads at a given
13 target error rate for every zone is generated. Thus, in this manner,
14 BPI/frequency capability histograms for every zone at a specified target error rate
15 are constructed. If the histogram of BPI capability at a target error rate of every
16 zone is not available, interpolation/extrapolation is performed to construct
17 histograms for the intermediate zones.

18
19 The constructed histograms are used to calculate cumulative performance
20 distribution functions (CDF) of the head frequency (e.g., BPI) capability at a given
21 target error rate performance metric) as input to the format optimizer. Such
22 performance distribution functions are designated as marginal, individual or per
23 zone distributions. In one example the distribution functions include one-
24 dimensional (1-D), two-dimensional (2-D) and three-dimensional (3-D) joint
25 BPI/frequency capability CDF, calculated at the same specified target error rate.
26 Marginal or one-dimensional distribution functions from the joint distribution
27 functions can also be calculated.

28
29 A version of estimating performance (e.g., frequency capability)
30 cumulative distribution functions at a given desired target performance metric
31 and zone is described. A number of frequency format profiles can be generated

1 and tested on a set of disk drives to ensure proper operation. The frequency
 2 formats are generated and used to exploit every head's linear density or
 3 frequency/BPI sensitivity at every zone. Thus, for example, the linear density
 4 sensitivity of every head at a ZoneK (K ranges from 1 to M zones) is determined.
 5 To do so, the performance of every head is measured (after full drive read/write
 6 and servo calibration/optimization) at each frequency at ZoneK. If Freq1_K,
 7 Freq2_K, ..., Freq6_K are the selected frequencies at ZoneK, in the
 8 measurement process, every head is positioned on a track (e.g., the same track)
 9 at ZoneK and the record/playback performance of each head is measured at
 10 every frequency using a performance metric of choice (e.g., off-track symbol
 11 error rate (SER)).

12
 13 For example, FIG. 2B shows the on-track SER performance of a selected
 14 head e.g. Head1, at Zone1, and the best least square polynomial fit curve. For a
 15 desired on-track target SER of $6e-7$, the BPI capability of the (randomly) selected
 16 Head1 at that target performance metric can be projected by extrapolating the
 17 data (interpolation is performed if the desired on-track target SER is in the
 18 performance range, and extrapolation is performed otherwise). FIG. 2B shows
 19 the projected BPI capability of that head at an on-track SER of $6e-7$ (i.e., 6×10^{-7}).
 20 The original nominal kBPI (i.e., before the application of vertical zoning) is also
 21 shown. The head can be classified as a strong head because there is a
 22 reasonably significant amount of margin before the on-track SER performance of
 23 this head can be changed from its nominal frequency/kBPI of ~ 188 with an on-
 24 track (log of) SER of -9.1 to a projected on-track (log of) SER of -6.22 operating
 25 at a frequency/kBPI of ~ 217 . Hence, there is a total kBPI gain of ~ 29 , allowing
 26 increase in the nominal frequency by 15 % while meeting the desired target on-
 27 track SER performance metric of $6e-7$ (i.e., 6×10^{-7}). Thus, for example, Head1 of
 28 disk drive3 has a frequency capability equal to 217 at an on-track SER of $6e-7$
 29 (i.e., 6×10^{-7}), which is noted for Head1 as one sample for generation and
 30 extraction of empirical histograms.

1 Performing the above steps for all the heads of all the disk drives
 2 considered in the measurement process, allows extraction of the empirical
 3 histograms of frequency capability at on-track SER of $6e^{-7}$ (i.e., 6×10^{-7}) for such
 4 heads, as shown by example in FIG. 2D. The y-axis shows the number of heads
 5 that meet the interpolated/extrapolated (i.e., projected) frequency capability that
 6 is shown on the x-axis. The extracted (empirical) histogram can be used to
 7 estimate the probability cumulative distribution function. The width of each
 8 histogram 76 corresponds to a variance of the head performance histogram,
 9 wherein an objective of the present invention is to improve the disk drive yield
 10 and capacity, and as a result reduce that variance.

11
 12 FIG. 2C shows an example joint BPI distribution plot. Such BPI
 13 distributions may predict that, for example, 10% of the heads in the disk drives
 14 for which measurement was performed, can operate at a frequency density of 1.5
 15 x freq (wherein freq is a reference frequency), and 50% can operate at density of
 16 1.25 x freq, and 90% can operate at density of 1.0 x freq, and 99.9% can operate
 17 at density of 0.75 x freq, etc. Using the estimated frequency capability
 18 cumulative distribution functions at the target performance metric and every
 19 zone, the format optimizer determines the disk drive yield and capacity.

20
 21 FIG. 2C is an example of a 2-D joint (i.e. outer diameter (OD) and middle
 22 diameter (MD)) BPI cumulative distribution function (CDF) at a target
 23 performance metric (e.g. on-track symbol error rate of $6e^{-7}$). The x-axis shows
 24 the BPI capability of all heads (i.e. from all the disk storage devices considered in
 25 the measurement phase) at MD AND y-axis is the BPI capability of all heads at
 26 OD. The z-axis shows the (calculated) number of heads divided by the total
 27 number/population of heads i.e., an estimate of probability that those heads have
 28 a joint BPI capability at OD AND MD of less than or equal to any given desired
 29 values. BPI capability for e.g. at OD in the above description it is meant that
 30 while operating at (or below, i.e., if considering CDF) a given BPI, after full
 31 Read/Write and servo calibration and optimization, meeting a desired given

target performance metric of choice at OD. Thus, the aforementioned description of BPI capability can similarly be extended to joint BPI capability.

Format Optimizer process

The format optimizer process block 66 comprises a variable BPI optimization process for solving multiple (e.g., three) constrained optimization problems given the inputs: number of frequency formats (i.e., desired number of different read/write frequencies), number of heads in each disk drive, and said BPI distributions. The first problem maximizes drive yield while preserving the same drive capacity, the second problem maximizes the drive capacity while preserving the same drive yield and the third problem maximizes drive yield while allowing reduced/relaxed TPI such that the desired target drive capacity can be met.

The format optimizer 66 inputs said BPI distributions, a desired disk drive capacity, the total number H of heads per disk drive and the number N of frequency profiles or vertical zones (i.e., frequency per zone across a media surface stroke). Given the frequency capability distribution of heads at a target performance metric, the total number of vertical frequency formats (F), the total number of heads per drive (H) and the nominal drive capacity, the format optimizer 66 simultaneously searches through all possible continuous range of frequency capabilities to maximize the drive yield such that the desired nominal drive capacity is met. The format optimizer 66 can also solve the same problem, but the drive capacity and drive yield interchanged.

As such, in one example, the format optimizer 66 optimizes high/low density as a function of zone, to improve the drive yield and meet a fixed target capacity. The format optimizer also optimizes capacity while achieving a fixed nominal drive yield, wherein the nominal yield is before the application of vertical zoning according to the present invention. In said example of F=2 formats (high density and low density) and H=8 heads 16 in a disk drive 100, the possibilities

1 include 1 head at high density and 7 heads at low density, 2 heads at high
2 density and 6 heads at low density, 3 heads at high density and 5 heads at low
3 density, 4 heads at high density and 4 heads at low density, 1 head at low
4 density and 7 heads at high density, 2 heads at low density and 6 heads at high
5 density, 3 heads at low density and 5 heads at high density, etc. Hence, the
6 format optimizer considers all the combinatorial possibilities, and in each case
7 solves a constrained optimization problem and finally chooses the best optimal
8 solution amongst all the possibilities. Alternatively, the format optimizer can be
9 designed to reach the best optimal solution more directly by solving a (non-linear)
10 mixed integer programming.

11
12 Therefore, once the 1-D, 2-D and 3-D joint BPI/frequency capability CDFs
13 (discussed above) at a given target performance metric are calculated and
14 passed as input to the format optimizer, the format optimizer solves the above
15 two problems, namely: (1) maximizing or improving the drive yield (i.e., due to the
16 pre-selected performance metric, e.g., off-track SER) while meeting a desired
17 nominal drive capacity and (2) maximizing the disk drive capacity while meeting a
18 desired nominal drive yield.

19
20 The format optimizer then mathematically casts the two problems stated
21 above as constrained optimization problems and solves them using well-known
22 optimization techniques such as e.g. line search algorithm. The constrained
23 optimization problems can also be cast as (non-linear) mixed-integer
24 programming and solved using existing methods in optimization theory.
25 Example constraints to be considered, and cast mathematically within the format
26 optimizer, include not exceeding a certain frequency at OD due to ASIC data rate
27 limitations or at ID due to head/media limitations. Furthermore, closed form
28 equations are derived and used in the format optimizer to estimate the actual
29 drive yield and drive capacity. A Format Generator process, described below, is
30 utilized to calculate the actual drive capacity after including all possible

overheads, such as adding and including redundant bits due to error correction coding or gray coding.

The format optimizer uses the information from the format generator, such as the calculated format efficiency per zone (i.e., defined in percentages as the amount of user data e.g. in blocks that can fit in all tracks in a zone), or number of tracks per zone, to achieve a very close estimate of disk drive capacity calculation as determined by the format generator. Then, the format optimizer calculates optimal linear density format profiles as well as optimal number of heads allocated to each vertically zoned format profile.

As an example, histograms are extracted and corresponding distributions are estimated for different zones at desired target error rates (e.g., for Zone1 at a target error rate of $1e^{-6}$, Zone2 at a target error rate of $1e^{-6}$, Zone3 at a target error rate of $1e^{-6}$, etc.) as described above. A format design is provided for 4-head disk drives ($H=4$), and 2 vertical frequency format/profiles ($F=2$), wherein the disk drive yield is optimized while meeting a minimum capacity requirement.

Without the method of the present invention (vertical zoning), conventionally when the same frequency is used per head per zone, if one of the 4 heads is a weak performing head having an error rate measurement e.g. $1e^{-5}$ at Zone1 (higher than the target error rate), that disk drive is failed. With the application of the present invention in that case, the format optimizer allocates the 3 other heads to higher frequencies, and allocates the weak head to a lower frequency at Zone1. The recording/playback performance of the weak head is compensated for, such that the minimum capacity requirement is met. As such, the format optimizer utilizes the performance distributions to determine two or more optimal frequencies per zone, and the optimal number of head allocations to those frequencies per zone such that constraints such as required disk drive yield and/or capacity are met.

1 For example, the format optimizer uses the estimated 1D, 2D and 3D joint
2 frequency/BPI capability distributions at a desired target performance metric to
3 jointly optimize for vertically zoned frequency format profiles and the
4 corresponding number of head allocations three zones at a time. An advantage
5 of considering three zones, as compared to only one (thus considering a joint
6 optimization versus individualized optimization), is that joint optimization allows
7 optimization of format profiles (e.g., frequency profiles) across the stroke on each
8 disk surface. Therefore, in this way we exploit the potential correlation in
9 performance from one zone to another as well as their individual and weighted
10 contribution to the overall surface capacity. A joint optimization approach is
11 preferable for a low/high density format layout across the stroke for either
12 improving the drive yield while keeping the same drive capacity, or improving the
13 drive capacity while preserving the same drive yield.

14
15 The generated results from the format optimizer include: the target
16 high/low BPI formats per zone, (optimal) number of head allocations per
17 format/layout and an estimate of the drive yield and capacity. The accuracy of
18 the estimates can be sensitive to the underlying extracted (joint) BPI distributions
19 at a given (on or off-track) error rate. Further, the target high/low BPI formats
20 can be sensitive to the variance of the (extracted) BPI distributions. And, the
21 variance of the BPI distribution can be sensitive to the absolute value of the (on
22 or off-track) target error rate and the choice of metric (e.g. error rate vs. MSE). In
23 addition, because the design of target high/low BPI formats are performed three
24 zones at a time and the yield improvement (while preserving the same overall
25 drive capacity) is based on the profile of the target nominal formats, the format
26 optimizer allows for a smoothing operation in order to smooth the target variable
27 BPI format designs if so desired. The format generator determines the number
28 of tracks per zone, the number of blocks per track, the radius at each zone, as
29 well as block and track format efficiency. This information is saved in e.g. output
30 files for use with the format optimizer. The format optimizer then saves the

1 design of target high/low BPI formats per zone that it generates, in two separate
2 files that can be read and loaded as input files into the format generator.

3
4 Once the target format profiles are calculated, if they are non-smooth
5 across the stroke, optionally a smoothing process is applied. The format profiles
6 are then loaded into the format generator 68 described below, to create vertically
7 zoned formats and configuration pages. The formats and configuration pages
8 are used by the disk drive firmware to create binary files to be loaded onto the
9 reserve image of the drives as part of the file system. FIG. 2A shows the
10 communication between the format optimizer 66 and the format generator 68. In
11 this fashion the design and implementation of format profiles, as well as the
12 number of optimal head allocations are performed off-line and are predetermined
13 for every drive configuration.

14
15 An example of format optimization for designing vertically zoned low and
16 high frequency profiles for disk drives with 4 heads (i.e., Head1 through Head4
17 corresponding to Surface1 through Surface 4 of Disk1 and Disk2) is described.
18 In this example, every disk surface is (uniformly) partitioned into three zones
19 across the stroke, with a fixed number of tracks (TPI) per zone, vertically aligned
20 from one surface to another. The nominal surface capacity (before the
21 application of vertical zoning) can be approximated by the sum over all zones of
22 the products of nominal tracks per zone by the nominal frequency per zone and
23 by the format efficiency per zone. Format efficiency per zone is a percentage of
24 all the user data that is effectively stored per zone. Then the nominal disk drive
25 capacity is equal to the nominal surface capacity multiplied by the total number of
26 surfaces (or heads). The nominal number of tracks per zone and the format
27 efficiency per zone can be generated and obtained from the format generator
28 (described further below).

29
30 Performing vertical zoning to e.g. improve the drive yield without losing
31 any nominal (disk drive) capacity, finds the best frequency per zone and per

1 head such that the disk drive meets performance and capacity requirements. As
2 such, if a disk drive with 4 heads fails test process performance limits due to e.g.
3 performance of Head1 at Zone1, but Head1 at Zone2 (or another head such as
4 Head3 at Zone1) performance is significantly better (i.e., passing the test limits
5 with reasonable margins), then a higher frequency than nominal at Zone2 or
6 Zone1 is designed for heads that are stronger (i.e. high density heads), and
7 instead the frequency at Zone1 for heads that are weaker (i.e. low density heads)
8 is lowered. This tradeoff is performed such that the overall disk drive capacity is
9 preserved, to obtain a vertically zoned design of variable frequencies per zone.
10 In addition, the number of heads (e.g. per zone) allocated to high or low density
11 is determined. Thus, the disk drive capacity can be approximated by the sum
12 (over all zones) of the products of number of low density heads per zone by low
13 frequency per zone by format efficiency per zone plus the (sum over all zones of
14 the) products of number of high density heads per zone by the number of high
15 frequency heads per zone by the format efficiency per zone.

16
17 In one version, the format optimizer solves for the above problem as
18 follows. The format optimizer is provided with the (joint) frequency capability
19 cumulative distribution functions (extracted and estimated from all heads
20 considered in the measurement process above) at a desired target performance
21 metric (i.e., the same targets used in the test process). Then, for every
22 combinatorial possibility of head allocation (e.g. to high or low frequency) the
23 format optimizer searches through a continuous range of possible frequencies,
24 by considering every zone independently (i.e. using the marginal distributions)
25 and by combination of zones (i.e. using the joint distributions), to maximize the
26 disk drive yield calculated using a closed form equation, such that the disk drive
27 capacity after the application of vertical zoning is essentially the same as the
28 nominal disk drive capacity. Further, the (optimal) low and high frequency
29 profiles for every combination of head allocations is compared and the one that
30 results in the highest value of (calculated) disk drive yield is chosen and passed

1 to the format generator for the generation of vertically zoned configuration pages
2 to be used by the disk drive firmware.

3
4 The surfaces of disks can be partitioned to more than the example three
5 zones above. The above steps of determining the optimal variable frequencies
6 per zones are useful to consider more than three zones. To reduce
7 computational complexity and time, if the selected/designed number of zones per
8 surface in a disk drive is more than three, the format optimizer can be used to
9 generate low and high frequency profiles three zones at a time and, suitable
10 smoothing operations are used to smooth the profile after post-processing.
11 Another approach includes embedding the smoothing operator in the design and
12 extend the joint optimization to all zones so as to consider the effect and impact
13 of smoothing to drive yield (calculation) as part of design rather than later stages.

14
15 In the above 4-head disk drive example, disk drive yield is maximized
16 while preserving the same nominal disk drive capacity. To determine the number
17 of head allocations, the format optimizer begins with one low density head and
18 three high density heads (e.g., per zone). The format optimizer searches through
19 a continuous range of possible frequency capabilities per zone, as well as two
20 and three zones at a time, by considering and using the 1D (i.e., marginal), (joint)
21 2D and 3D distributions that result in the best calculated value of the drive yield
22 such that a minimum nominal drive capacity can be obtained. Next, the format
23 optimizer uses two low and high-density heads and repeats solving the same
24 constrained optimization problem. This process is continued until all the
25 combinatorial possibilities are considered. Finally, the format optimizer chooses
26 the solution that results in the best calculated value of the drive yield and
27 provides the target low and high (optimal) density format profiles and the
28 associated number of high and low head allocations to the format generator. The
29 format generator then generates vertically zoned format files and configuration
30 pages to be used by the firmware.

Format Generator

In one embodiment, the format generator process block 68 is used for embedded servoing (i.e., servo position is generated by reading back written information from the disks, such as servo wedges in which position information is embedded on the disks, and that information is used to position the head on the disk surfaces).

For example, the format generator 68 described herein generally performs three functions including utilizing target formats/frequencies (or linear densities/BPI) for each zone as an input, and performing an exact calculation of the capacity of each zone and the disk drive itself. Further, the format generator 68 calculates the format efficiency (percent of the disk area that is occupied by customer data) for each zone. The third, and primary purpose of the format generator 68 is to generate configuration page data. The configuration pages contain per-drive, per-zone, and per-head-per-zone parameters that are programmed into disk drive electronics components. Such components include the disk controller, the read/channel, and the preamplifier. The parameters are ordered such that the disk drive firmware selects the correct set of parameters to be programmed into each of the components for the particular head and zone that is being written to or read from at the time.

The format generator 68 calculates the exact frequency and the exact capacity of each zone taking into consideration limitations in the programmability of the components and limitations of the capabilities of disk drive components. Some examples of component limitations include: read channel synthesizer frequencies are limited to a discrete collection of frequencies; preamplifier (not shown) has a minimum and a maximum delay in turning on its write current; the down track separation between the head read and write elements (not shown) varies from component to component; the reference crystal (not shown) has finite accuracy and stability over temperature; the spindle motor driver can keep the spindle motor speed within a finite precision of the nominal rotational speed;

1 the controller has specific latencies in generating commands to the read channel
2 and preamplifier, often with a finite uncertainty as to the exact timing of these
3 commands, etc.

4
5 The format generator 68 can be fully automated, or can be directed by a
6 human specialist. In the absence of input from the format optimizer 66, the target
7 per-zone BPI/frequency profiles, in particular, must be generated from human
8 input. In general, the human specialist modifies the target frequency profiles until
9 the desired capacity is reached.

10
11 In one embodiment, the format generator 68 includes a format efficiency
12 process that uses the format optimizer's target low/high variable BPI format
13 designs as well as the optimal predetermined number of low/high performing
14 head allocations, to modify and generate the appropriate configuration pages
15 (i.e., as part of the file system). For each zone, the format generator 68 selects
16 the nearest frequency to the target frequency for that zone, given the component
17 limitations and programmability mentioned above. The nearest frequency
18 comprises the target formats.

19
20 The optimal predetermined number of low/high performing head
21 allocations comprises the number of heads allocated to each of the multiple
22 frequencies in each zone. The format optimizer 66 determines the head
23 allocation, which is input to the format generator 68. The capacity of a zone
24 depends both on the target frequencies and the number of heads allocated to
25 each frequency.

26
27 The format optimizer uses the nominal average BPI or frequency (nominal
28 BPI format target designs) (e.g., one read/write frequency) in each zone as input
29 from the format generator 68 to estimate the disk drive yield before applying
30 variable BPI designs. For a design with multiple frequencies per zone, this is the
31 weighted average (by the number of allocated heads) of the multiple frequencies.

1 The nominal format is created by e.g. a human operator working with the format
2 generator 68 in the interactive manner described above.

3
4 The format generator 68 performs calculations of number of tracks per
5 zone, number of blocks per track, radius at each zone as well as block and track
6 format efficiency to calculate the drive zone capacity. The format optimizer 66
7 estimates the capacity using the tracks per zone, radii, and format efficiency.
8 Thus, the format optimizer and the format generator interact as shown in FIG. 6.
9 For example, for 4-head disk drives, and 2 density format frequency profiles (i.e.,
10 high and low frequency profiles) with 3 zones across the disk surface, after the
11 measurement and optimization processes, the format generator 68 is provided
12 with 2 optimal frequency profiles and optimal allocation of the heads. The format
13 generator 68 then calculates capacity, and if the drive capacity meets the
14 minimum required capacity, then the format generator generates configuration
15 files/pages for the disk drive firmware. The configuration pages are used by the
16 drive firmware to command the head to write at an assigned frequency to a zone.
17 If the calculated drive capacity does not meet the minimum required capacity,
18 format optimization is performed again with new format efficiency values, and the
19 process is repeated.

20 21 Head format assignment and selection criterion

22 The process for allocation of numbers of heads to each of the
23 predetermined multiple frequencies in a zone, and the process of assignment of
24 a particular head in a particular disk drive to a frequency, are distinct. First the
25 allocation process is performed by the format optimizer 66, and applies to disk
26 drives of a particular design (product). Then, the assignment process is
27 performed during manufacturing as part of a test process undergone by each
28 disk drive to be produced. This section describes the assignment process task.

29
30 Once the configuration pages are generated and converted to binary files
31 as part of the file system, they can be loaded and saved in a reserved image of

1 the disk drive for use after power cycling. Then, for every disk drive, the
2 following example assignment process is performed per head and per zone, to
3 determine assignment of a certain predetermined number of heads to high BPI
4 formats and the remaining heads to low BPI formats in a 2 frequency design, to
5 satisfy allocation of heads to said formats by the format optimizer 66.

6
7 The assignment process for the example 2 frequency format where high
8 and low frequencies are used, includes the steps of:

9 1. Load default parameters from the configuration pages, and
10 calibrate selected parameters on a per head, per zone basis (e.g., load high BPI
11 format profile for all zones across the stroke);

12 2. Take measurements from all heads at all the disk surfaces at pre-
13 selected zones with respect to a metric, e.g., mean square error, on/off track
14 error rate, etc.;

15 3. For each head in every measured zone, sort/rank the heads by the
16 performance metric from best to worst; select a pre-specified (by the allocation
17 process in the format optimizer 66) number of heads with the best performance,
18 and assign those heads to the higher frequency for a particular zone;

19 4. Optionally interpolate between the measurements obtained from
20 the pre-selected number of zones to find the results for the other zones, and do
21 the same for the interpolated zones. The interpolation operation in a version of
22 the present invention reduces test process time. Head performances are
23 measured, sorted and assigned to a frequency for a subset of the total number of
24 zones. For the remaining zones, the heads are assigned by interpolating on the
25 head assignments made from measurements;

26 5. For every zone, save the worst pre-specified number of bad (i.e.
27 low performing) heads with respect to the selected metric; and

28 6. For every zone, load and calibrate all the bad heads with the lower
29 BPI format.

The above process can be used to improve yield, improve capacity, and trade off between yield and capacity. In a test, the heads can be passed or failed with respect to a metric (e.g., off track error rate) to determine if the test target limits are met.

The servo firmware is extended to load more than one format profile. A head can be assigned a different read/write frequency per zone across a disk surface, and radially similarly situated zones on different disk surfaces can have different read/write frequencies assigned to the corresponding heads whereby one head is assigned a different frequency/format profile than another head.

The example assignment process described herein applies to a format design with two recording frequencies per zone. However, the process can be easily extended to more than two frequencies per zone, wherein the process can be iterated upon to assign heads to more than two frequencies per zone, as described by an example below. For a design with H heads and F frequencies per zone, above steps 1 and 2 are completed for the high frequency. The first selection of heads in step 3 assigns the highest h_1 heads, where h_1 is the pre-specified number of heads allocated to the highest frequency for that zone. The remaining $(H - h_1)$ heads are then loaded and calibrated with the second highest frequency (step 1 again), measurements taken (step 2 again), and the heads ordered relative to the metric and the best h_2 heads are assigned to the second highest frequency (step 3 again). Here h_2 is the pre-specified number of heads allocated to the second highest frequency in the zone. Steps 1-3 of the process are then iterated for the $(H - h_1 - h_2)$ heads, followed by the $(H - h_1 - h_2 - h_3)$ heads, and so on, until h_F heads remain to be assigned to the lowest frequency. The set of $\{h_1, \dots, h_F\}$ heads comprise the head allocation made by the format optimizer 66.

Table 1 below illustrates the result of an example of the vertical zoning head assignment process on a disk drive with 6 heads and 5 zones across the

stroke on each disk surface. Each head is assigned to either high or low density format based on record/playback performance of that head, wherein as discussed above, the number of heads assigned to low density and the number of heads assigned to high density is according to the head allocation results determined by the format optimizer.

| HEAD # | FORMAT\ZONE ZONE 1 | ZONE 2 | ZONE 3 | ZONE 4 | ZONE 5 |
|--------|-----------------------|--------|--------|--------|--------|
| 0 | Low | High | Low | High | Low |
| 1 | High | Low | High | High | Low |
| 2 | High | Low | High | Low | High |
| 3 | High | High | Low | High | High |
| 4 | Low | High | High | High | High |
| 5 | High | High | High | Low | High |

Table 1 – An example for the format assignment of a disk drive after test process, using vertical zoning with variable BPI across the zones.

FIGs. 3-6 show example steps of an embodiment of the above processes. Referring to FIG. 3, an example vertical zoning data collection process includes the steps of:

- (1) Select a number of disk drives for data measurement/collection process (step 300);
- (2) Create nominal linear density profile KFCI (i.e., nominal_KFCI): $\overline{kFCI}(R)$, wherein R is disk radius (step 302);
- (3) Create more linear density profiles by multiplying the nominal_KFCI

$$(1 \pm x_i) * \overline{kFCI}(R)$$

by scaling factor x_i , (step 304):

- (4) Create binary file system for every generated profile (step 306), i.e. for

$$i \in \{1, \Lambda, N\}$$

wherein N is the total number of frequency format profiles. For example, for N=2, having X_1 , and X_2 , if $X_1=0.05$ and $X_2=0.1$, then including the nominal frequency format itself, there are 5 different frequency profiles in step 304, as follows: (a) nominal_KFCI, (b) $1.05 * \text{nominal_KFCI}$, (c) $0.95 * \text{nominal_KFCI}$, (d) $1.1 * \text{nominal_KFCI}$, and (e) $0.90 * \text{nominal_KFCI}$ (wherein "*" is the multiplication operator);

(5) Select the first head by setting i to 1(step 308);

(6) Load file system i onto the reserved image of the disk drives (step 310);

(7) Take head performance measurements (e.g., (on/off) track MSE and SER measurements) (step 312);

(8) Unload and save the results in the Data Base (step 314);

(9) Increment i by one ($i=i+1$) (step 316);

(10) is $i = N$? (step 318)

If not, go to step 310, else done.

The above process collects performance data for all the heads at all zones.

Referring to FIG. 4, an example vertical zoning post-measurement processing and per zone BPI distribution extraction process includes the steps of:

(1) Organize the performance data (e.g., MSE and SER) obtained above, for every head $i \in \{1, \Lambda, M_1\}$ and every zone $j \in \{1, \Lambda, M_2\}$ as a function of linear density samples, wherein in this example M_1 is the total number of heads in the disk drives selected for the measurement process (e.g., 40 disk drives each including 4 heads, results in total of $M_1=160$ heads), and M_2 is the total number of zones, to generate head performance histograms (step 400);

(2) Choose a target performance metric (e.g., MSE or SER) (step 402);

(3) Set $j = 1$ and $i = 1$ (step 404);

- 1 (4) Interpolate/Extrapolate BPI at the specified target performance
2 metric (e.g., MSE or SER) for head i at zone j (step 406);
- 3
- 4 (5) Select the next head by incrementing i by one ($i = i + 1$) (step 408);
- 5
- 6 (6) Is $i = M_1$? (i.e., have all heads been processed?) (Step 410);
- 7
- 8 (7) If not, got to step 406 to process the next head, else generate
9 frequency capability histogram at that given zone j for all the heads (step 412);
- 10
- 11 (8) Is $j = M_2$? (i.e., have all zones been processed?) (Step 414);
- 12
- 13 (9) If yes, stop;
- 14
- 15 (10) Otherwise, move to the next zone and start with the first head
16 again, whereby $j = j + 1$, $i = 1$ (step 416), and go to step 406 to repeat.
- 17

18 The above process generates (1D) frequency capability histograms at a
19 target performance metric and for every zone by considering all the heads from
20 the sample disk drives selected in the measurement process. Using the (1D)
21 frequency capability histograms at a given target performance metric, techniques
22 in probability theory known to those skilled in the art can be adopted to estimate
23 the (1D) frequency capability distributions. Further, the above procedure above
24 is extended (i.e., by using 2D and 3D interpolation/extrapolation routines), to
25 extract and estimate the 2D and 3D joint frequency capability histograms and
26 their associated distributions.

27
28 Referring to FIG. 5, an example head assignment process for a two
29 frequency format ($N=2$, high/low density) design, includes the steps of:

- 30 (1) Assign all n heads in a disk drive to the first selected format (e.g.,
31 high-density format) (step 500);
- 32 (2) Calibrate all n heads at high-density format for selected zones (step
33 502);
- 34 (3) Measure performance metric at selected zones for all n heads (step
35 504);
- 36 (4) For each selected zone, rank heads by metric (step 506);

- 1 (5) For each selected zone, assign highest K heads to high-density
- 2 format, other n-K heads to low density (step 508);
- 3 (6) Optionally interpolate head assignment for remaining zones (step
- 4 510); and
- 5 (7) Complete calibration of all heads and all zones at assigned formats
- 6 (step 512).

7

8 The above process completes assignment of each head in each disk drive

9 to a predetermined frequency.

10

11 As shown in FIG. 2A, information is passed between the format generator

12 68 and the format optimizer 66, wherein initially, the format generator 68 passes

13 information including e.g. track layout to the format optimizer 66 to have a more

14 accurate way of calculating capacity (nominal format). Such information and

15 constraints are provided to the format optimizer 66 to solve said joint optimization

16 problems. The format optimizer 66 performs a coarse calculation of capacity,

17 whereas the format generator 68 performs an exact calculation of capacity. The

18 format generator performs functions of providing format information (e.g., number

19 of tracks per zone, and zone layout) to the format optimizer 66, and calculating

20 exact format capacity. Such information is passed once from the format

21 generator 68 to the format optimizer 66 for a design (e.g., 4 head design). The

22 format generator 68 initially provides nominal information to the format optimizer

23 66, wherein the format optimizer 66 performs its calculation of target densities

24 (zone frequencies and number of heads allocated to each frequency) and

25 provides that information to the Format Generator. The format generator 68

26 then determines if required capacity has been reached. Adjusting target

27 densities to meet yield and/or capacity requirements includes adjusting selected

28 zone density or zone frequencies.

29

Referring to FIG. 6, an example Format Generator/Format Optimizer iteration process for minimum capacity requirement C, and a user specified allowed overcapacity Delta, includes the steps of:

- (1) Determine disk geometry, track density (TPI) and servo wedge details, and output inner diameter (ID) and outer diameter (OD) radii; TPI; number of servo wedges, and wedge length (step 600);
- (2) format generator 68 generates initial format at capacity using the values ID, OD radii, TPI, number of wedges and wedge length, and outputs radius of each zone per disk surface, number of tracks per zone, number of blocks per track, and format efficiency by zone (step 602);
- (3) format optimizer 66 generates optimal target densities at all zones as described above, and outputs frequency density targets (e.g., low/high BPI) by zone, and number of frequency density (e.g., low/high BPI) head allocations by zone (step 604);
- (4) format generator 68 generates new formats with Capacity (i.e., number of logical blocks per disk drive) (step 606);
- (5) If Capacity > C and Capacity < (C + Delta) (step 608), then stop;
- (6) Otherwise, adjust target densities (Step 610), and go to step 606.

In one example, surface capacity is described by the equation: $TPI \times BPI \times (1 + ECC) / FE$, wherein TPI is track density, BPI is the linear density, ECC is the fractional level of error correcting code used which is typically about 0.1, and FE is the format efficiency which is typically about 0.57.

The above process completes the format generation process.

As an example scenario of the results generated by an embodiment of vertical zoning according to the present invention, a set of 32 matured disk drives are selected wherein each disk drive includes 12 heads. The 1D, 2D and 3D joint BPI empirical distributions are extracted at a given specified target on track error rate from three pre-specified radial zones, i.e., outer, middle and inner

zones. Next, the extracted distributions are fed into the format optimizer, and low or high frequency per zone format designs obtained at the three specified zones. This is performed once by individual optimization, all based on 1D distributions at each of the three zones, and once by joint optimization based on the measurements obtained from the three zones and their extracted 1D, 2D and 3D distributions. The head format allocation search process (VZ test) is performed in a simulation, wherein for each zone the one-format designs (i.e. before the application of vertical zoning) are a special case of two-format variable BPI designs by forcing low and high formats to be the same and equal to the nominal BPI format at that zone. Furthermore, the pass/fail of disk drives is decided based on the criterion that each head at every zone pass a given on-track target error rate as well as off-track squeeze and un-squeeze offset margins. Then, the drive yield is calculated (i.e., in simulation by interpolation/extrapolation of the measurement data) before and after the application of vertical zoning. The following Table 2 summarizes the results:

| | <u>Using Joint Optimization</u> | <u>Using Individual Optimization</u> |
|-------------------------------|---------------------------------|--------------------------------------|
| Drive Yield (Yd) | 93.75 | 90.625 |
| Drives failed after VZ | 4 & 29 | 4, 6 & 29 |
| Drives recovered | 2, 3, 13, 19, 21 & 25 | 2, 3, 13, 19, 21 & 25 |
| Passed drives failed after VZ | None | 6 |
| Drives failed before VZ | 2, 3, 4, 12, 19, 21 & 29 | 2, 3, 4, 12, 19, 21 & 29 |
| | i.e., drive yield before VZ | i.e., Drive yield after VZ |
| | Yd=75% | Yd = 75% |

Table 2

In addition to disk drives, the present invention is useful with other storage devices such as e.g. tape drives, optical drives, etc. Though a manufacturing test case for a two format design is described, the search algorithm can easily be generalized to higher number of formats. The design of two formats based on 1D, 2D and 3D joint storage density BPI distributions can easily be generalized to higher order or dimensions by considering more zones than three. The design of formats can be generalized from two to higher number of formats. The measurement procedure can be generalized to consider more zones as well as off track measurements such as 747 curves or quality metric versus error rate

1 measurements to perform correlation study for the choice of best metric with less
2 potential test time.

3
4 Further, the above methods for a per zone variable BPI design can be
5 easily extended to a variable BPI/TPI design as described below. The
6 measurement process is extended to further include 747 measurements of all the
7 heads from a pre-selected number of disk drives. To speedup the measurement
8 of raw data, instead of 747 measurements, off-track and adjacency margin
9 (squeeze measurements) of all heads can be performed. Once the 747 raw data
10 of all heads at pre-selected number of zone locations is determined, for every
11 zone (joint) BPI/TPI distributions can be extracted at given desired target(s) by
12 post-measurement processing of data. The choice of target is an integral part of
13 the amount of performance gain, such as disk drive yield, due to per zone
14 variable BPI/TPI designs. Some example choices of target(s) are off-track error
15 rate, the variance of position error signal or even a combination of both. After the
16 joint BPI/TPI distributions are extracted and available for all zones, a per zone
17 variable BPI/TPI design can be obtained by solving two-constrained (joint)
18 optimization problems: one that maximizes the drive yield while keeping the
19 same drive areal density and another that maximizes the drive areal density
20 while keeping the same drive yield. Once the per zone variable BPI/TPI designs
21 are obtained, a head BPI/TPI allocation and selection criterion, similar to that
22 described herein, can be used such that a pre-selected number of heads are
23 allocated to high and low density BPI and TPI formats, for example, for the case
24 of two variable BPI/TPI per zone design performed as part of test process.

25
26 The present invention improves drive yield and drive capacity (or
27 consequently areal density at a fixed target BPI), and allows reducing the target
28 TPI by increasing the average BPI across the stroke per head (depending on the
29 number of formats considered) to meet a desire target drive capacity. In
30 particular, due to a maximum deliverable data rate of the ASIC components (e.g.,
31 channel, controller and preamp) the BPI at the outer diameter may be limited by

1 the minimum deliverable data rate of the mentioned ASIC components. For
 2 example, if the controller is capable of maximum deliverable data rate of 650
 3 MHz, the preamp capable of 700 MHz and the channel capable of 750 MHz, then
 4 the BPI at the outer diameter is limited by the controller at a maximum
 5 deliverable data rate of 650 MHz. Thus, a conventional one format BPI profile
 6 across the stroke does not achieve the desired drive capacity and the desired
 7 manufacturing drive yield. The target BPI is increased and the BPI profile across
 8 the stroke is relaxed, wherein according to the present invention, the per zone
 9 variable BPI design can be used to design (variable BPI) target formats that meet
 10 the desired drive capacity at a fixed target TPI while improving the overall drive
 11 yield.

12
 13 Referring back to FIG. 2A and FIGs. 3-6, in one embodiment of the
 14 present invention, the steps of the example method of the present invention: (1)
 15 the data collection/measurement process block 62, can be implemented on
 16 general purpose computing equipment 61, known in the art, and drive electronics
 17 including special purpose electronic circuit (e.g., logic circuit) 49 and on board
 18 microprocessor 57 (FIG. 1B), configured according to the present invention,
 19 wherein the special purpose electronic circuit 49 is configured to perform the
 20 measurements, the on board microprocessor 57 directs the special purpose
 21 circuit 49, and transfers the data to the general purpose computer 61, (2) the
 22 head assignment process can be implemented on the on board microprocessor
 23 57 within the disk drive 100 configured according to the present invention,
 24 wherein a data collection subtask is related to the head assignment task such
 25 that the data collection sub-task is performed by the special purpose electronic
 26 circuit 49 within the disk drive 100, (3) the steps in each of the data processing
 27 block 64, the format optimizer block 66 and the format generator block 68 can be
 28 implemented on general purpose computing equipment 61 (e.g., high end PC,
 29 PC server or workstation, etc., including programmable simulation software)
 30 configured according to the present invention.

1 The present invention has been described in considerable detail with
2 reference to certain preferred versions thereof; however, other versions are
3 possible. Therefore, the spirit and scope of the appended claims should not be
4 limited to the description of the preferred versions contained herein.